SCIENTIFIC LITERATURE REVIEW

THE ENVIRONMENTAL IMPACTS OF BARRIER ISLAND BREACHING WITH PARTICULAR FOCUS ON THE SOUTH SHORE OF LONG ISLAND, NEW YORK

Report Prepared for:

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SEPTEMBER 1993

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1. INTRODUCTION

1.1 *Authorization*

On January 15, 1993 Governor Cuomo established a task force to recommend long-term and short-term approaches to cope with continuing and potential storm damage to the Long Island, Westchester, and New York City coasts. This report was authorized by the State of New York Department of State (project C000154) to provide information to the task force that will be considered in making their recommendation to the Governor.

1.2 *Project Scope*

This report summarizes the findings of a review of existing scientific literature concerning the environmental impacts of new inlet breaches to the barrier island, bays and mainland shoreline of barrier island systems. The specific area of interest is the south shore of Long Island, New York. However, pertinent studies of similar geomorphic areas along the remainder of the U.S. East Coast, the Gulf Coast, and locations outside the U.S. were also considered.

1.3 *Background*

Long Island's south shore barrier beach has had a history of new inlet formation caused by storms and subsequent closure due to natural sedimentary processes (Taney, 1961; Caldwell, 1972; U.S. Army Corps of Engineers, 1983; Leatherman and Allen, 1985). Based on this history, it appears likely that storms will open new inlets in the future. In fact, at the time of this report an inlet breach into Moriches Bay formed by a December 1992 northeast storm was in the process of undergoing artificial closure by the U.S. Army Corps of Engineers. The formation of that particular inlet has been popularly attributed to the effect of erosion control works (i.e., the Westhampton Beach groin field) on the down-drift segment of the shoreline, which resulted in substantial erosion and loss of barrier width at the precise location of the breach. Improper coastal engineering also contributed to the 1980 breach just east of Moriches Inlet. In this latter case, the dredging of a bay-side channel directed ebb currents against the back side of the barrier, causing severe erosion and narrowing at the location that was subsequently breached (Kassner and Black, 1982b). Based on these two recent events, it appears that man's efforts to control the natural system on the south shore of Long Island may actually have increased the chances for barrier island breaching in this area.

Prior to 1953, when Moriches Inlet was reopened after two years of closure, a period of inlet stability on Long Island's south shore barrier extended back to the opening of Shinnecock Inlet during the 1938 hurricane and the opening of Moriches Inlet in 1931. As discussed above, two new inlets formed recently (i.e., in 1980 and 1992), both of which breached the barrier fronting Moriches Bay. In addition, a breach occurred at Westhampton Beach in early March 1962 due to extreme high water levels caused by an intense northeast storm (U.S. Army Corps of Engineers, 1963). In all three cases, the breaches were closed by artificial means (with the closure of the most recent breach currently in progress). However, the decisions to seal the new inlets were made under emergency conditions, with an incomplete knowledge of the environmental impacts and/or benefits associated with barrier breaching. This report is intended to provide the initial scientific information base for decisions regarding the fate of future inlet breaches.

2. METHODOLOGY

2.1 *Information Sources Used*

This investigation entailed a review of the existing scientific literature concerning the environmental impacts of barrier island breaches. Information sources that were reviewed ranged from articles published in scientific journals and technical texts, to unpublished manuscripts and miscellaneous other "grey literature". Experts in the field of inlet research were contacted to identify sources of scientific literature; however, oral comments regarding the subject were not included in this report.

The references cited in this study were obtained from a variety of sources. Many of the documents were drawn from Cashin Associates' technical library, particularly those that are specific to the south shore of Long Island. The New York State Department of State also provided several important documents.

In an effort to identify additional documents that may be pertinent to the issue at hand, Cashin Associates contacted a number of scientists and agency representatives whose work has included inlet studies. The names of additional contacts were obtained from individuals on the initial list of contacts, thereby establishing a network for identifying as many useful sources as possible. However, due the time constraints of this project, it is likely that some knowledgeable persons have been inadvertently overlooked. A number of other persons were identified as potential sources of pertinent information, but could not be reached, or were contacted but were unable to provide assistance due to other priorities. In particular, several university professors indicated that their time through the beginning of September would of necessity be devoted to course work for the new school year. Appendix A contains a list of persons who were contacted during the course of this investigation.

In addition, the resources of a number of libraries and document depositories were utilized during this investigation. These are listed in Appendix B.

2.2 *Limitations of Existing Information*

Tidal inlets have been an important topic of scientific research since the 1800s. However, most studies have focused on the physical properties of specific inlets, particularly with respect to geomorphology, hydrodynamics, sedimentary processes, inlet stability and other engineering aspects (U.S. Army Corps of Engineers, 1976; Weisher and Fields, 1985). It became evident shortly after the commencement of this literature search that relatively few studies have been undertaken specifically to address the impacts that inlets have on environmental conditions. Furthermore, it appears that studies of this type which have been undertaken are less likely to be reported in scientific journals, and are relegated in large part to the "grey literature" (which includes such documents as masters theses, Ph.D. dissertations, unpublished manuscripts, government agency reports, and reports prepared by private consultants). In comparison to journal articles, grey literature is generally more difficult to obtain. Additionally, grey literature is typically not subject to the same level of scientific scrutiny and, therefore, can be more likely to contain suspect methodologies. However, the non-journal documents that are cited in this report are the product of organizations (e.g., the U.S. Army Corps of Engineers, leading universities, and research institutions) that are acknowledged as having reliable scientific expertise. Any document that presented findings or conclusions that did not appear to be based on valid scientific methodology or that appeared to be conjectural was not included in this report.

Although some studies regarding the environmental impacts of barrier breaching and inlet formation have been undertaken on Long Island's south shore, these documents are not plentiful. In accordance with the scope of work outlined by the Department of State, therefore, this literature search included investigations of other areas that are geomorphically similar to Long Island, including various locations along the Eastern Seaboard (particularly Massachusetts, Virginia, and South Carolina), the Gulf Coast (particularly Florida and Texas), and Canada. However, it is important to note that the effects of a barrier breach are very site-specific, and observations that have been made in one geographic area are not necessarily directly applicable to another area, due to differences in tidal regime, freshwater input, long-shore sedimentary transport processes, and other factors. In fact, the environmental consequences of the formation of a new inlet through the Long Island barrier beach could vary dramatically, depending on the exact location of the breach. Therefore, caution should be used in interpreting the information contained in this report in terms of its applicability to a specific future inlet breach that may occur on Long Island's south shore.

2.3 *Contents of the Remaining Sections of the Report*

The remainder of this report is a summary of pertinent information that was uncovered during the course of the investigation. The physical impacts of inlet breaching (i.e., in terms of tidal flushing, salinity, temperature, tidal range and storm surge, and the tidal flow of adjacent bays) are discussed in Section 3. The effects that new inlets have on coastal processes (i.e., in terms of storm wave energy and erosion, littoral drift, and barrier island migration), as well as the effect that breach stability has on the magnitude of the potential impact, are discussed in Section 4. The impacts to the bay ecosystem, with particular reference to shellfish, finfish, and wetlands, are discussed in Section 5. Miscellaneous impacts, including those related to navigation and economic factors, are discussed in Section 6. Finally, Section 7 presents a synopsis of the identified impacts, segregated into categories on the basis of whether the impact is beneficial, detrimental, neutral or variable.

3. PHYSICAL IMPACTS

3.1 *Tidal Flushing*

Tidal inlets serve as conduits for the exchange of water between the bay and the ocean. The creation of a new inlet through the barrier beach will generally increase the rate at which bay water, which receives runoff and associated contaminants from the adjacent uplands, is flushed with clean ocean water. However, this cause and effect relationship between inlet creation and improved tidal exchange is not always as pronounced as is generally assumed. For example, in 1972 the Corpus Christi Water Exchange Pass was artificially cut through the Mustang Island barrier to Corpus Christi Bay, Texas. As the name suggests, one of the primary objectives of the Pass was to increase water exchange between the bay and the Gulf. Although the Pass significantly influences bay water in its immediate vicinity, the effect on water exchange in Corpus Christi Bay as a whole appears to have been to be small (Behrens, et.al., 1977).

There is ample direct evidence that the opening and closing of Moriches Inlet during this century has affected the rate of tidal flushing and the accumulation of contaminants in Moriches Bay. The closure of the inlet in 1951 caused a significant increase in pollutant levels in Moriches Bay, but did not cause a noteworthy change in pollution conditions in Great South Bay, despite the substantial amount of tidal exchange between the two bays. The eastern part of Bellport Bay, which is situated at the easternmost end of Great South Bay, in closest proximity to Moriches Bay, did exhibit some increase in pollutant levels. The lack of a significant effect on water quality in the main body of Great South Bay may have been the result of complex near-shore hydraulics in Moriches Bay (Redfield, 1952), and points out that blanket generalizations of the water quality benefits of new inlets should be applied cautiously.

The reopening of Moriches Inlet in 1953 increased the volume of tidal exchange between Moriches Bay and the ocean, and reduced pollution concentrations in the bay; phosphorus levels, in particular, experienced a dramatic decrease. In addition, the reopened inlet resulted in increased dissolved oxygen and decreased dissolved organic matter in both Moriches Bay and Bellport Bay (Bumpus, et.al., 1954).

The effect of a breach into a bay already served by an inlet would generally be beneficial in terms of tidal flushing and the water quality of the bay. A modeling study undertaken by Pritchard and DiLorenzo (1985) indicates that the tidal range in Moriches Bay would increase substantially under various scenarios of inlet breaching (see further discussion in Section 3.4). Those results show that a breach would increase the volume of ocean water introduced into the bay during each flood tide and would increase the volume of bay water flushed to the ocean during each ebb tide. Consequently, it is reasonable to conclude that the breach configurations included in the analysis would result in improved average water quality in the bay. The effect that a Moriches Bay breach would have on the adjacent bays was not included in the investigation.

An important aspect of the water quality of Long's Island's south shore bay system is coliform bacteria concentration, which is utilized to classify these waters in terms of shellfish harvesting status. Coliform bacteria are introduced into the bays almost entirely through stormwater runoff (LIRPB, 1978). Even though no scientific literature was uncovered during this investigation which specifically addresses the effect that inlets have on coliform concentrations, it is reasonable to conclude that inlet-induced enhancement of tidal flushing in the bay could improve bacterial water quality in shellfish growing areas, based on investigations of other contaminants derived from runoff (e.g., those studies discussed above with respect to the opening and closing of Moriches Inlet).

3.2 *Salinity*

The salinity in the barrier lagoons on Long Island's south shore is controlled primarily by two factors: the rate of freshwater input from streams and groundwater flow, and the rate of tidal exchange with the ocean. In general, the opening of a new inlet through the barrier beach will increase the salinity of the bay due to the resulting increase in tidal exchange with the saltier waters of the ocean. During the period between 1952 and 1977, variations in the volume of water exchanged between Great South Bay and the ocean was the major influence operating on the annual average salinity in the bay (Hollman and Thatcher, 1979).

The magnitude of the change in salinity caused by an inlet breach will depend on numerous factors, but will typically be most pronounced for bays that previously lacked a direct connection to the ocean. For example, the opening of an inlet into Moriches Bay in March 1931 resulted in a large increase in salinity, which diminished as the inlet tended to close over the next decade (Glancy, 1956). The opening of Moriches Inlet also had a profound impact on salinity in Shinnecock Bay and eastern Great South Bay (including Bellport Bay), which are both hydraulically connected to Moriches Bay. The reopening of Moriches Inlet in 1953, following a period of closure that commenced in 1951, caused the salinity at the western end of Moriches Bay to more than double within six weeks (Turner 1983). This mirrors the salinity changes in Bellport Bay that were observed before and after the 1931 opening of Moriches Inlet (Woods Hole Oceanographic Institute, 1951).

Bay salinity will also increase in the event of a breach into an embayment that is already directly connected to the ocean. The occurrence of a breach to the immediate east of Moriches Inlet in 1980 caused salinity in the western portion of Moriches Bay to increase by an estimated 4 to 5 parts per thousand (ppt), thereby creating a more uniform salinity distribution throughout the entire bay (Turner 1983). Furthermore, even the modification of the configuration of an existing inlet which results in enhanced tidal flow will tend to cause increased salinity in the bay. A modeling study of Great South Bay indicated that the dredging of Fire Island Inlet in 1970 increased bay-wide average salinity by almost one ppt, under mean tide conditions and median freshwater inflow (Pritchard and Gomez-Reyes, 1986).

3.3 *Water Temperature*

Since salinity is the chemical parameter that generally has the greatest effect on marine organisms, studies reviewed during this investigation concerning biological impacts have emphasized the effect that increased tidal mixing has on bay salinity. Temperature is also an important physical parameter of the bay water that can be altered by barrier breaching, but has generally been overlooked by these studies.

The increased tidal exchange resulting from the formation of a new inlet would cause the temperature of the bay to approach the temperature of the ocean, similar to the effect on salinity that is described in Section 3.2. Because the bay is warmer than the ocean during most of the year (except in the coldest parts of the winter, when portions of the bay can freeze), a breach would cause a decrease in the average temperature of the bay (Turner, 1983). Thus, the increased tidal exchange between the bay and ocean caused by an inlet breach would have a moderating effect on seasonal extremes in bay temperature by keeping these waters cooler in the summer and slightly warmer in the winter; however, scientific data were not available to directly confirm this effect.

3.4 *Tidal Range and Storm Surge*

The tidal range in a back-barrier bay is largely controlled by the efficiency with which the inlet(s) transfer the tidal wave into the bay. In general, the friction that water encounters as it flows through a tidal inlet prevents the bay from filling to the level of the ocean during high tide and prevents the bay from emptying completely at low tide. Therefore, the tidal range in the bay is less than the ocean tidal range. The opening of a new inlet through the barrier island would allow ocean water to more completely fill the bay during the flood tide, and to drain more completely from the bay to the ocean during the ebb tide.

For example, during the period that Moriches Inlet was closed between 1951 and 1953, the tidal range in Moriches Bay was only ±0.2 foot (Czerniak, 1976). The present tidal range in Moriches Bay (i.e., prior to the formation of the inlet breach in December 1992) has been reported to be ±0.7 feet (Turner, 1983). The tidal range in Chatham Harbor was increased by approximately one foot as a result of the 1987 breaching of the Nauset Beach barrier on Cape Cod, Massachusetts (Giese, 1988).

A hydrodynamic modeling study undertaken by Pritchard and DiLorenzo (1985) assesses the impact to Moriches Bay of various barrier breach configurations, including the 1980 breach, in terms of increased flooding risk for bay-shore properties due to elevated tidal ranges and increased transmittance of coastal storm surges into the bay. This study is important in that it appears to be the only published simulation of the hydrographic response of Long Island's south shore bay system to inlet breaching. Therefore, some details of the model (e.g., inputs, outputs, gridding, assumptions, etc.) are given here.

The Pritchard-DiLorenzo (1985) study utilized the two-dimensional, finite element "CAFE" model, which was originally developed at the Massachusetts Institute of Technology, and was subsequently adapted to such water bodies as the Moriches-Great South Bay system by the Marine Sciences Research Center (MSRC) of the State University of New York at Stony Brook. The model simulates both current velocities and sea surface elevations throughout the interior of the bay based on data inputs consisting of bay geometry (configured as a triangular grid network), and sea surface elevations at the ocean side of the inlet. Geometrical data were obtained from navigation charts, aerial photographs, and bathymetric surveys undertaken in 1981 by MSRC. Tidal elevation and phase data were obtained from National Ocean Survey (NOS) tide gauge records. Model simulations of storm surge elevations utilized NOS storm surge data. Frictional coefficients were estimated through a series of model calibration runs, with values assigned to achieve optimal agreement between observed and numerically computed sea levels and currents.

The Pritchard-DiLorenzo study (1985) utilized a "nesting" procedure to reduce the number of grid elements and, thereby, reduce computing costs. This technique, which is commonly used in hydrographic models, involves the computation of average boundary conditions during initial computer runs. In this case, the initial grid included all of Great South and Moriches Bays, while only Moriches Bay and Moriches Inlet were included in later runs. The underlying assumption in this nesting procedure is that slight errors in the boundary conditions will not adversely affect simulated results at locations far from the boundary.

The results of the Pritchard-DiLorenzo (1985) modeling analysis revealed that the degree to which a storm surge is transmitted to the bay under normal conditions (i.e., a single, more or less centrally located inlet) depends upon the duration of the storm surge. Short period surges, like those associated with hurricanes, are attenuated by the existing inlet and are not completely transmitted to the bay, which causes the surge height to be higher at the inlet than in the further reaches of the bay. Long period surges, like those caused by typical winter storms, pass more completely through the existing inlet, resulting in surge heights throughout the bay that are closer in magnitude to the surge height at the inlet. Thus, the formation of a new inlet would not have a significant effect on bay-side floodwater heights for long-period storm events (Pritchard and DiLorenzo, 1985).

Tanski and Bokuniewicz (1989) concluded, on the basis of the results of the Pritchard-DiLorenzo (1985) modeling study, that a large breach through the Moriches Bay barrier would increase normal tidal ranges in Moriches Bay by about 60 percent, and that short-period (hurricane) floodwater elevations would increase by 35 to 40 percent. The Pritchard-DiLorenzo (1985) model also indicates that a breach-induced increase in tidal range and floodwater height would not be symmetrically distributed throughout the bay. A breach to the east of Moriches Inlet would cause a slightly greater increase in tidal range and floodwater height in the eastern basin of Moriches Bay than in the western basin. Conversely, a breach to the west of Moriches Inlet would cause tidal range and floodwater height to increase to a greater degree in the western basin.

The Pritchard-DiLorenzo (1985) model shows that a relatively large fraction of the combined tidal wave and storm surge are transmitted to Moriches Bay under existing conditions. This is because water depth through the inlet is greater during a storm surge, which results in a lesser degree of attenuation of the surge/tidal wave passing into the bay (compared to the shallower water conditions in the inlet during normal tidal cycles).

3.5 *Tidal Flow Characteristics of Adjacent Bays and Inlets*

The bays on the south shore of Long Island are hydraulically connected by canals and narrows, as is common along most of the barrier island system of the Eastern Seaboard and Gulf Coast. Consequently, events that affect the tidal flow in one bay are likely to affect the tidal characteristics of the adjacent bays and inlets. For example, the opening of a stable inlet directly into Shinnecock Bay during the 1938 hurricane decreased tidal flow through Moriches Inlet, causing the latter inlet to lose scouring power. As a result, Moriches Inlet shoaled until it eventually closed in 1951 (Kassner and Black, 1981). The literature also indicates that during the period after Moriches Inlet reopened in 1953, the tidal flow through Shinnecock Inlet decreased (Czerniak, 1976). A similar inter-relationship between hydraulically connected inlets has been noted for the barrier island chain along the west-central coast of Florida (Davis and Gibeaut, 1990). On the basis of these investigations, it is reasonable to conclude that the rate of shoaling has accelerated in Moriches Inlet (and in Shinnecock Inlet, to a lesser degree) during the time that the 1992 Moriches Bay breach has been open.

The stability of Shinnecock Inlet is affected by the tidal flow that passes through Moriches Inlet and, to a lesser extent, through Fire Island Inlet. Some scientists (Kassner and Black, 1983) have concluded that if nature were allowed to take its course, Shinnecock Inlet would probably close because of its tendency to shoal under normal tidal conditions (i.e., without considering the influence of the presently active breach to Moriches Bay). Any further decrease in tidal flow through Shinnecock Inlet resulting from a breach that captures some of the bay's tidal prism would accelerate that trend. Thus, the barrier beach/bay system as a whole tends to self-regulate, in the sense that an increase in tidal exchange in one portion of the bay (as would occur in the event of an inlet breach) will cause a compensating decrease in tidal exchange in another portion of the bay.

The opening and closing of inlets can also affect the progression of the tidal wave through hydraulically connected bays. For example, the closing of Moriches Inlet in 1953 caused a delay in the timing of high tide in Moriches Bay because the tidal wave had to travel from Fire Island Inlet (Redfield, 1952). In addition, during periods when Moriches Bay has been closed, the net tidal flow through Narrow Bay is from Moriches Bay to Great South Bay. When Moriches Inlet is open, the net tidal flow reverses (Kassner and Black, 1982b).

The presence of inlets in a stretch of barrier beach minimizes the possibility of new inlet formation because the existing inlets allow storm surge waters to drain more quickly to the ocean. Lacking inlets, the surge waters escaping from the bay would have a greater chance of cutting a breach through a narrow section of the barrier (Leatherman, 1989).

4. IMPACTS ON COASTAL PROCESSES

4.1 *Storm Waves and Mainland Erosion*

There does not appear to have been any scientific investigations to determine the degree to which an inlet breach on Long Island's south shore would cause increased erosion of the mainland shoreline due to enhanced transmittance of storm waves into the bay. There have been anecdotal reports that the December 1992 breach of the Westhampton Beach barrier has resulted in higher wave energy at the Remsenburg shoreline across the bay. However, no valid scientific reports on this topic were uncovered during this literature search.

A detailed study (Giese, et.al., 1989a and b; Fessenden and Scott, 1989; Giese, 1988; Wood, 1991) has been undertaken with respect to an inlet breach that occurred in January 1987 on the Nauset Beach barrier, opposite the Town of Chatham, Massachusetts (which is situated at the elbow of Cape Cod). One of the main impacts associated with that event was the significantly increased erosion of the Chatham shoreline segment opposite the breach, due to increased wave energy in the bay. This erosion problem was particularly acute during late 1987 and early 1988, but subsequently has abated (probably due to shoaling related to the formation of the flood tidal delta - see Section 4.2 for a description of flood tidal delta formation, and refer to the final paragraph in this section for further discussion regarding the effect that water depth has on wave erosion).

In all, the breach-induced erosion at Chatham greatly damaged ten shorefront properties, caused one house to fall into the harbor, and forced the removal of several others. A revetment that was placed along the affected shoreline actually resulted in accelerated erosion at some locations. It is predicted that over the next two to three decades there will be extreme shoreline changes, both erosional and depositional, along the inner shoreline of Chatham Harbor. After an initial period of north-south oscillation over short distances, the locus of maximum erosion will shift inexorably southward as the inlet migrates in that direction (Giese, et.al., 1989a and b).

It should be noted that the situation in Chatham differs in a number of important ways from conditions that prevail on the south shore of Long Island. Most importantly, the strength of the waves passing through the Nauset breach were not substantially attenuated in Chatham Harbor due to the position of the inlet channel, which brought deep waters in close proximity to the mainland shoreline, and due to the short distance (±3,000 feet) between the inlet and the mainland (Giese, et.al., 1989a and b). In contrast, Long Island's south shore bays are relatively shallow and wide throughout, except in the proximity of the existing inlet channels. Moriches Bay is approximately three to six feet in average depth and at least a mile wide at the location of the 1992 breach.

A steeply-sloped shoreline allows ocean swell to arrive without being slowed or changed until the last possible minute, resulting in waves (especially during winter storms) that abruptly rise up and break violently on the shoreline (Bascom, 1964). It is these short, steep waves that are primarily responsible for shoreline erosion (U.S. Army Corps of Engineers, 1977). In contrast, the shallow, gentle slope which is typical along the south shore of Long Island's mainland tends to reduce wave energy before it reaches the shore (Bascom, 1964). A study conducted along the Virginia coast concluded that the role of bottom friction in the dissipation of wave energy over the shelf was a critical factor in the difference in erosion rates along various segments of the study area (Kimball and Wright, 1989). The offshore zone at the northern end of the study area is characterized by shallower water and lower gradients, which cause the frictional dissipation of waves to be greater there compared to the deeper and more steeply sloped southern end of the study area. Since the waves at the southern end retain more of their energy as they approach the shore, shoreline recession is generally more rapid in that region.

4.2 *Littoral Drift*

On average, ocean waves strike the shoreline at an angle rather than head-on. As a result, the incident wave energy has a distinct component that is directed parallel to the shore, which results in the continuous transport of sand along the shoreline in a process that is commonly called littoral (or long-shore) drift. Along Long Island's ocean shore, the long-term net direction of littoral drift is generally from east to west.

The available evidence indicates that inlets serve as large sinks of sand in the nearshore system, which deprive down-drift beaches of the sediment supply that was delivered prior to the formation of the inlet (Taney, 1961; McCormick, 1973; LIRPB, 1989; Tanski and Bokuniewicz, 1989; Davis and Gibeaut, 1990). Sediment in the littoral drift system is carried into the bay by the flood tide, where this material accumulates into the flood tidal delta. Some sediment is moved back through the inlet during the ebb tide and is deposited offshore in the ebb tidal delta. The growth rate of these deltas is a measure of the amount of sand being trapped from the littoral drift by the inlet (Leatherman, 1982).

It was estimated that the flood tidal delta of Moriches Inlet accumulated 150,000 cubic yards of sand annually (Suffolk County Planning Department, 1982). Leatherman and Allen (1985) estimate that the total volume of sand present in the ebb and flood tidal deltas of Moriches Inlet is approximately one to two million cubic yards. During the eleven months that the 1980 Moriches breach was open, approximately 750,000 cubic yards of material were accumulated in the breach's flood tidal delta (and an unknown quantity in the ebb tidal delta), all of which was diverted from the long-shore sediment transport system (Research Planning Institute, Inc., 1985). An investigation of the ebb tidal delta of Moriches Inlet indicates that sediment starts to accumulate as soon as the breach occurs (Caldwell, 1972).

With the exception of the erosion that has been caused by the Westhampton Beach groin field, the loss of sand supply to down-drift beaches due to the effect of inlets is the most serious erosion problem on the south shore of Long Island (LIRPB, 1989). Because of the accumulation of littoral sand in an inlet's tidal deltas, this relationship between the existence of an inlet and consequent down-drift shoreline erosion holds true even if the sand-trapping effects of inlet jetties are ignored. For example, during the ±100 years prior to the opening of Shinnecock Inlet, the stretch of barrier between the present-day locations of Shinnecock and Moriches Inlet experienced an average shoreline erosion rate of approximately 1.2 feet/year. In contrast, the average shoreline erosion rate for this segment of barrier increased to approximately 8.2 feet/year during the period between the opening of Shinnecock Inlet in 1938 and the construction of the jetties in the mid-1950s (Tanski and Bokuniewicz, 1989). Black (1987) noted that during the first two years following the breaching of Shinnecock Inlet, the down-drift shoreline receded approximately 100 feet. Anders and Reed (1989) noted that average shoreline change along the South Carolina coast is consistently most variable and maximum shoreline change is greatest adjacent to inlets, with the zone of influence extending several kilometers up-drift and down-drift from the inlet.

The volume of littoral sediment removed into the tidal deltas of an inlet is a function of the tidal prism that passes through the inlet (Davis and Gibeaut, 1990). Inlets having relatively large tidal prisms (i.e., tide-dominated inlets) tend to have larger tidal deltas due to the greater force and volume of the tidal flow deflecting sand into offshore waters during the ebb tide and into the bay during the flood tide. Inlets with smaller tidal prisms (i.e., wave-dominated inlets) tend to have smaller deltas, especially on the ocean side of the barrier where waves rework and reintroduce the sand into the littoral drift system.

As discussed more fully in Section 4.4, an inlet will eventually close if the littoral sand supply exceeds the inlet's hydraulic capabilities, unless artificial measures (e.g., dredging) are taken to maintain the inlet. When an inlet becomes sealed, the sediment that has accumulated in the ebb tidal delta is reworked by waves and re-introduced into the nearshore sediment transport system (Greenwood and Keay, 1979), while the sediments in the flood tidal delta typically remain in place and serve as the substrate on which back-barrier wetlands and eelgrass beds are formed (see Section 5.4).

Importantly, active inlet breaches can sometimes cause severe deficiencies in littoral drift and induce increased shoreline erosion for distances that may extend for several miles in the down-drift direction (Bruun, 1960). These erosional problems can commence almost immediately after a new inlet forms, which condition was observed during studies conducted following the 1987 breaching of the Nauset Beach barrier on Cape Cod, Massachusetts (Giese, 1988).

The extent of erosion that occurs down-drift of a given inlet will be affected to some degree by the status of neighboring inlets. For example, the rate of growth of the Shinnecock Inlet flood tidal delta decreased during the period immediately following the 1953 reopening of Moriches Inlet. Concurrently, there was a decrease in the erosion rate of beaches situated down-drift from Shinnecock Inlet, which was attributed to a greater volume of material bypassing the inlet due to decreased tidal flow resulting from some of Shinnecock Inlet's pre-1953 tidal prism being captured by Moriches Inlet (Czerniak, 1976).

The impact that inlets have on down-drift locations can be exhibited in ways other than through increased shoreline erosion. Studies of historical maps and aerial photographs indicate that Democrat Point, at the western end of Fire Island, migrated almost five miles between the early 1800s and 1941 (when a stone jetty was constructed at that location to stabilize the position of Fire Island Inlet). During the period between 1931 and 1934 there was no advancement of Democrat Point, which Kassner and Black (1983a) attributed to the opening of Moriches Inlet in 1931 at the eastern end of Fire Island, and the removal of littoral sand into the associated tidal deltas (however, the three-year time frame may have been too short for this cause and effect relationship to be manifested). In a similar way, the formation of a new inlet breach would decrease the flow of sand into down-drift inlet channels (Taney, 1961).

The magnitude of the impact that a new inlet will have on down-drift locations is dependent on a number of variables, including the rate of littoral transport and the tidal prism that passes through the inlet, which together determine how long the inlet will remain open and how much sediment will be diverted into the inlet's tidal deltas (O'Brien, 1976). If the littoral drift is strong and the tidal prism is relatively small, a large portion of the sand will be bypassed down-drift and the inlet will tend to close quickly, which will cause less cumulative erosion of down-drift beaches. In contrast, breaches tend to remain open for longer periods of time if the volume of drift is small relative to the tidal prism of the new inlet (Bruun, 1960). This latter set of conditions causes larger volumes of littoral sand to accumulate in the new inlet's tidal deltas and accelerates down-drift erosion, but decreases the shoaling rate in down-drift inlet channels. Inlet breaches through the barrier beach of eastern Moriches Bay (including the breach that is currently being closed) may be more stable and persistent due to a diminished littoral sand supply related to the effect of the Westhampton Beach groin field (Bruun, 1960).

New inlets can have subtle, local effects on littoral transport. For example, one study of the Massachusetts barrier island system found that wave refraction around ebb tidal deltas at inlets can cause transport reversals that affect erosion/accretion rates in the vicinity of these inlets (Fitzgerald, et.al., 1978). An investigation of North Inlet in South Carolina undertaken by Finley (1978) showed that the ebb tidal delta at that location causes incoming waves to be refracted toward the inlet. This modification of the normal wave pattern results in a net annual littoral transport toward the inlet from both the north and south (the average regional long-shore transport direction is north to south). Such transport reversals due to the refraction of waves passing over an ebb tidal delta can have a significant effect on erosion rates at down-drift locations by causing sand to be trapped in the ebb delta complex, and thereby preventing the transport of this sand to down-drift beaches (Fitzgerald, 1980). The offshore flow of water in ebb tidal currents can also have some effect on the direction, steepness, and length of incoming waves, which may alter nearshore sediment transport processes (O'Brien, 1976).

Man's efforts to reduce the shoaling of inlet channels and to arrest the natural, down-drift migration of inlets has tended to further exacerbate erosion at down-drift beaches (Tanski and Bokuniewicz, 1989). Jetties have been constructed to stabilize the position of all of the permanent inlets through Long Island's barrier beach. The jetty on the easterly side of each inlet traps sediment that is carried in the littoral stream, thereby diminishing the supply of sand to down-drift beaches.

As discussed above, the opening and closing of a given inlet can have profound impacts on the status of down-drift beaches and inlets. In addition, the formation or closure of an inlet within a system will affect the sedimentation rate at hydraulically interconnected inlets. This effect will be manifested regardless of the relative position of the inlets up-drift or down-drift, due to the loss of tidal prism to the new inlet or the gain in tidal prism when an active inlet closes (Black, 1987).

4.3 *Barrier Island Migration*

Barrier island migration is the long-term, landward shift in the position of barrier islands over the continental shelf in response to sea level rise. In general, inlet formation, overwash, and wind transport are the three main processes which promote barrier island migration. Of these three processes, sediment transport through inlets is the most important mechanism in landward barrier retreat on Long Island (Leatherman, 1982 and 1989). Overwash is of secondary importance, serving mostly to supply sand to the back barrier, often at the expense of bay-side marshes. Wind transport is of minor importance to barrier beach migration on Long Island's south shore (Leatherman, 1989).

The historic record indicates that the inlets along the south shore of Long Island are geologically short-lived. Only Fire Island Inlet has persisted for more than a century. The other major inlets have lasted an average of about 50 years, and have been sustained by structural measures and maintenance dredging. Ephemeral inlets generally do not produce significant flood tidal deltas and, therefore, are less important than persistent inlets with respect to barrier migration (Leatherman, 1989). Migrating inlets are a particularly efficient means of landward barrier retreat via the construction of flood tidal deltas, because the flood tidal delta deposits are spread over a greater length of the back-barrier (Leatherman 1979).

A study of the rate of barrier island migration on Metompkin Island, Virginia, is consistent with the conclusions stated above (Byrnes, et.al., 1989). That study involved an examination of historical charts and maps, which revealed that southern portion of Metompkin Island retreated at a much faster rate than the northern portion of the island during the period between 1852 and 1988. These findings were attributed to the occurrence of frequent inlet breaches and the attendant enhancement of the landward transport of sediment on the southern portion of the island.

The Long Island barrier has maintained a fairly stable position relative to the mainland over a long time period, despite the continued rise in mean sea level that has apparently occurred (Tanski and Bokuniewicz, 1989). As is discussed above, this stability is due to maintenance projects at the major inlets, as well as the application of a general policy over the recent past to promptly close new inlet breaches. These actions have reduced the volume and spatial extent of flood tidal delta deposits, which retards the landward migration of the barrier. From a management standpoint, however, concerns regarding the disruption of barrier island migration caused by man's activities in the coastal zone must be balanced against the other, more immediate impacts associated with the formation of new inlets (LIRPB, 1989).

4.4 *Breach Stability Considerations*

Obviously, the magnitude of the impacts associated with the occurrence of a given inlet breach is a function of the length of time that the breach is open. A storm-induced inlet that closes shortly after its formation will affect environmental factors to a lesser degree than a breach that continues to widen after the initial breach.

The stability of an inlet is related to the ability of physical forces (especially tidal currents through the inlet, but also winds and waves to some degree) to maintain the channel versus the tendency of the inlet to close due to the supply of sediment from up-drift beaches (O'Brien, 1976; Leatherman, 1982; Davis and Gibeaut, 1990). The volume of sediment supply generally decreases with increasing distance from the headlands that serve as the primary source of this material. Thus, inlets that are closer to the headlands will, in general, require greater tidal action to remain open (Lucke, 1934).

Taney (1961) estimated that the annual littoral drift transport rate actually <u>increases</u> by 50 percent between Moriches Inlet (300,000 cubic yards per year) and Fire Island Inlet (450,000 yd^3/yr), indicating that a significant external source of sand is being introduced into the system between these two locations. Williams and Meisburger (1987) used mineral tracers to show that this additional sediment is being derived from sand deposits on the inner continental shelf. Those authors also indicate that the volume of littoral drift decreases steadily in a westward direction from Fire Island Inlet, to 420,000 yd^3/yr at Jones Inlet and 306,000 yd^3/yr at East Rockaway and Rockaway Inlets, which is consistent with the general rule by Lucke (1934) discussed above.

The position of an inlet relative to the geometry of the adjoining bay is an important factor affecting the amount of tidal prism that passes through the inlet and, thereby, will influence the stability of the inlet. For example, hydraulic modeling performed by the University of Florida (1973) showed that the re-establishment of Navarre Pass on the northern Gulf coast of Florida would not draw a sufficient tidal prism to keep the inlet open unless engineering works were implemented. In contrast, the same numerical methodology showed that Rollover Pass through the barrier at Galveston, Texas, would draw a sufficient tidal prism to keep the inlet open during normal climatic conditions. The difference in the stability of these two inlets was attributed to the geometry of the respective bay-inlet systems. Navarre Pass cuts the barrier at the approximate center of a long, narrow sound. Friction retards the movement of the tidal wave in the sound, resulting in a relatively small tidal prism passing through the inlet. Rollover Pass, in contrast, is situated at the end of a wide arm of Galveston Bay, which results in a lower degree of friction and a relatively larger tidal prism flowing through the inlet (University of Florida, 1973).

The width of the barrier through which an inlet breach is cut is also an important factor determining the stability of the inlet, as indicated by a study of Brown Cedar Cut on the Texas coast (Mason and Sorensen, 1971). The subject inlet opens/closes and migrates in response to natural physical processes, with minimal artificial controls. Between 1930 and 1969, the barrier beach in the vicinity of the cut experienced significant erosion (i.e., total recession of more than 650 feet). The narrowed barrier width resulted in a more stable channel, due to reduced frictional resistance acting on tidal currents flowing through the inlet. The previous, longer inlet lost scouring energy because of greater friction with the channel sides and bottom.

In general, new inlets that are cut on the Long Island barrier beach tend to shoal to closure within a relatively short period of time (Taney, 1961). Tidal prism calculations based on tidal velocity measurements made for the 1980 breach into Moriches Bay indicated that the breach did not appear to be adequate to maintain the cross-sectional area of the inlet/breach system (Sorensen and Schmeltz, 1982; Schmeltz, et.al. 1982). On this basis, the authors of the referenced studies concluded that the breach was probably unstable toward closure. It was further concluded that, given the inlet history at this location and in the absence of human intervention, the end result may have been complete closure of the connection between Moriches Bay and the Atlantic Ocean (i.e., both the breach and original inlet may have closed).

The 1987 Nauset breach is an example of new inlet that was allowed to evolve naturally, based on the mistaken premise that it would quickly be sealed by coastal processes (Wood, 1991). The initial breach channel through Nauset Beach was only 18 feet wide and ±one foot in depth. These relatively diminutive dimensions, coupled with the history of breach openings and closings along this section of barrier, led local agencies to believe that the breach would close naturally. However, atypical hydrographic conditions caused the breach to expand steadily over the next fifteen months to greater than one mile in width (Giese, et.al., 1989a), and increased erosion became a problem on the mainland shoreline segment that had become exposed to ocean waves passing through the new inlet (see Section 4.1).

Another example of an inlet breach that was allowed to take its natural course involved the barrier beach at the southwest end of Nantucket Island, Massachusetts. The problems induced in this case included navigational hazards and the burial of productive clam beds due to shifting sands in the flood tidal delta of a new inlet that was cut in 1961. However, this breach was left alone, and in 1976 natural processes started to cause shoaling within the inlet channel. The breach gradually filled in over the next nine years, and closed completely in 1985 due to waves and currents caused by the passage of Hurricane Gloria. Twice since 1985 storms have breached the barrier at the same location, but in both cases long-shore transport quickly sealed the new breach (which is normally what happens at this location). This case is cited as an example of solving a breach-related problem by doing nothing (Tiffney and Benchley, 1987).

Even an inlet that is hydraulically stable, whereby normal tidal currents are sufficient to keep the channel open, will tend to migrate in response to littoral processes (Leatherman, 1982). The net direction of this migration will be the same as the direction of net long-shore drift. Prior to the construction of jetties, the stable inlets on Long Island's south shore historically had migrated substantial distances to the west (Taney, 1961). Thus, it is expected that a persistent inlet breach in the subject barrier system will also migrate westward, either by: ***(a)*** the lengthening of the up-drift barrier and concurrent erosion of the down-drift barrier, which results in an inlet that is oriented perpendicular to the shoreline (e.g., Jones, Moriches and Shinnecock Inlets); or ***(b)*** the lengthening of the up-drift barrier without erosion of the down-drift barrier, which results in an inlet that is oriented parallel to the shoreline (e.g., Rockaway, East Rockaway, and Fire Island Inlets).

5. BIOLOGICAL IMPACTS

5.1 *Shellfish*

The potential impacts that inlet breaching can have on shellfish are related to the changes that such an event induces in the various physical parameters that have been discussed above. For example, shellfish populations will respond in a certain way to altered bay salinity caused by a breach. Breach-related changes in bay water temperature, tidal flushing (and its influence on water quality), and coastal processes may also have some impact on shellfisheries within the affected bay(s).

To provide clarity, the following discussion has been organized on the basis of each of the four applicable parameters noted above. However, it is important to note that any given breach will result in a complex combination of physical changes to the bay, and that some of these changes may have opposite effects on shellfish (e.g., compare the impacts discussed below with respect to increased salinity versus increased tidal flushing). Therefore, the reader is cautioned that focusing on the effect of a single parameter can lead to an erroneous conclusion about the overall impact on shellfish.

A. Impacts Related to Tidal Flushing

In an often-cited study of the shellfishery of Shinnecock, Moriches and eastern Great South Bays, Glancy (1956) states that during the years 1946 through 1951, with the flow through Moriches Inlet greatly restricted, "small form" algae populations boomed. These algae dominated the water column, but did not serve the nutritional needs of the resident clams and oysters. In addition, the algae supported the growth of the worm coral, *Hexagonus hydroides*, which encrusted the exterior of the living oyster shells. The result of these circumstances was that oyster populations, which significantly decreased following the opening of Moriches Inlet in 1931 (see Section 5.1.B below), were further impacted during the 1940s. Between 1951 and 1953, when Moriches Inlet was closed, "small form" concentrations were the heaviest ever, and extended throughout Moriches and Shinnecock Bays, and even into Great South Bay as far as Fire Island Inlet.

Glancy (1956) attributes the subsequent recovery of the clam fishery in Great South Bay to the timely reopening of Moriches Inlet in September 1953. Water sampling throughout the three bays showed a marked increase in salinity and decrease in "small form" concentrations during the five months following the reopening of the inlet. The changes in Great South Bay were most dramatic at its eastern end, closest to the new inlet. The newly opened inlet also caused the worm coral infestation to disappear.

The response of the shellfisheries in Great South Bay and Moriches Bay to the 1951 closing and 1953 reopening of Moriches Inlet is also documented in a series of reports produced by Woods Hole Oceanographic Institute (Woods Hole Oceanographic Institute, 1951; Redfield, 1952; Bumpus, et.al., 1954; Ryther, et.al., 1957; Ryther, 1958; Guillard, et.al., 1960). The main objective of these investigations was to identify the ultimate cause of the early 1950s crash in the shellfish populations of these two bays. However, the findings also have bearing on the issue of how the formation (and closure) of inlets affect the biological resources of the bay.

The Woods Hole investigations revealed that the closing of Moriches Inlet in 1951 caused a decrease in the tidal flushing of Great South and Moriches Bays, resulting in a dramatic increase in the levels of nitrogen and phosphorus (see Section 3.1). These nutrients were derived from fecal wastes flowing freely into Moriches Bay from numerous duck farms that were situated along the shoreline.

Increased tidal flushing generally promotes accelerated clam growth, as measured by shell size (Greene, 1978). The growth rate of individual specimens in Great South Bay was found to be greatest in the vicinity of Fire Island Inlet, due to an increased supply of oxygen and food at that location compared to stations in the bay's interior. The maximum size attained was also greatest in the areas of highest tidal flows. However, other factors related to proximity to the inlet also have some degree of influence over clam growth. The higher salinity and sandier sediments which characterize portions of the bay in the vicinity of the inlet are both conducive to clam growth (Greene, 1978) - see Sections 5.1.B and D for further discussion.

An increased rate of tidal exchange resulting from the creation of a new inlet would not necessarily have a strictly beneficial effect on shellfish populations. Excessive flushing would lead to a high loss of the planktonic shellfish larvae to ocean waters and, consequently, could result in poor setting and a gradual decrease of the stock. The large tidal variations and high flushing rates of South Oyster Bay and Hempstead Bay may partly account for the low abundance of seed clams in those bays because too many larvae are flushed out of the inlet (USEPA, 1981). A similar situation may also exist in Moriches Bay, which has a relatively low level of clam productivity, despite a high rate of clam growth. Moriches Bay has a large tidal exchange relative to its volume, and the residence time of its waters may be less than the planktonic larval stage of the hard clam, although this has not been precisely determined (COSMA, 1985). Thus, it is evident that there is an optimal level of flushing with respect to the shellfish ecology of a given embayment, and any increase in tidal exchange beyond that level could have an overall detrimental effect on the shellfishery.

B. Salinity-Related Impacts

A basic principle of estuarine ecology is that salinity is a primary factor in limiting upstream penetration of many species. Shellfish predators tend to be fairly intolerant of lower salinities, and are restricted to the high salinity zones of estuaries. Many bivalves, such as the hard clam (*Mercenaria mercenaria*) and the eastern oyster (*Crassostrea virginica*), are tolerant of lower salinities and thrive in the fairly narrow range of salinities that are too low for survival of any shellfish predators and competitors but not low enough to have serious adverse effects on their own physiology, survival and reproduction. An increase in salinity within an estuary has the potential of making the environment more suitable to a range of shellfish predators, which can result in an expansion of the zones in which these predators are present and can lead to greater predation of hard clams and other bivalves (USEPA, 1981 and 1982).

Between the early 1800s and 1931, practically no clams were marketed from the eastern Great South Bay. Oysters would reproduce and set in this area, but would grow slowly and generally would not be "fat" due to low salinities. The western bay was more suitable for growth at that time due to higher salinity, but the oyster seeds were rapidly destroyed by predators (Glancy, 1956; Van Popering and Glancy, 1947).

After the creation of Moriches Inlet in 1931, oyster drills (which are restricted to more saline waters) invaded the bays and destroyed the oyster sets year after year. The remaining oysters were growing vigorously and attaining large size. Clams, which are less affected by drills, set and grew to market size all throughout these areas. Glancy (1956) concluded that if oyster drills could have been controlled economically, it would have been possible to double oyster production in Great South Bay compared to the situation prior to the opening of Moriches Inlet, due to salinity conditions that were favorable for growth. Van Popering and Glancy (1947) concluded that the clam population in Great South Bay experienced an overall benefit from the breach.

A series of studies was undertaken by a variety of agencies, including the U.S. Environmental Protection Agency (1981 and 1982), to assess the impacts to the hard clam fishery in Great South Bay and South Oyster Bay resulting from the sewering of southern Nassau County and the southwestern portion of Suffolk County. Prior to the installation of sanitary sewers, sanitary wastes from homes in the service areas were discharged (via septic systems and cesspools) to the shallow groundwater aquifer, which eventually discharges to the bay. Sewering decreased the bay's freshwater input by diverting a large volume of water to outfalls on the ocean side of the barrier, resulting in increased bay salinity. Since an inlet breach through the barrier would also be expected to result in a salinity increase in the bay, the findings of the USEPA studies are pertinent to the present investigation.

The USEPA (1981 and 1982) studies found that the increased salinity resulting from the sewering projects could cause an overall increase in the populations of certain clam predators that are sensitive to lower salinities. These include the following:

- channeled whelks (*Busycon canaliculatum*), which utilize clams below the cherrystone size as its major food source, except where alternate prey are abundant - whelks are one of the only predators that can feed on adult clams, which can be significant because relatively few clams survive to adult size, and the loss of a single adult is comparable to the loss of many young

- Moon snails (*Polinices duplicatus* and *Lunatia heros*), which feed almost exclusively on bivalves, and are the most serious predators of adult hard clams in areas where their temperature and salinity requirements are met

- Calico crabs (*Ovalipes ocellatus*), which can be voracious predators of hard clam seeds

- Oyster drills (*Eupleura caudata* and *Urosalpinx cinerea*), which were found to be the largest single cause of predation of seed clams in the study area, accounting for 27 percent of all empty clams recovered during the survey - oyster drill distribution is highly related to salinity gradients within an estuary

The USEPA (1981 and 1982) studies determined that the populations of other hard clam predators would not be significantly augmented by the bay salinity increase resulting from the sewering projects. These include the following:

- Mud crabs (*Neopanope sayi* and *Panopeus herbsti*), which are already the most abundant predators in the study area

- Blue crabs (*Callinectes sapidus*), which are potentially significant predators of hard clams, but also have a wide salinity tolerance range

- Common Rock crabs (*Cancer irroratus*), which are significant predators of young hard clams under laboratory conditions, but are not abundant in the study area

- Horseshoe crabs (*Limulus polyphemus*), which are not affected by the salinity range in estuaries

- Starfish (*Asterias forbesi* and *Asterias vulgaris*), which are voracious predators of oyster and bay scallops, and also consume clam spat and slightly exposed adults - starfish are generally not abundant in the study area, and are probably limited to the cooler deeper channels by the high summer temperatures in the bay

- Hermit crabs (*Pagurus longicarpus* and *Pagurus pollicaris*), which laboratory studies have indicated are predators of young hard clams, but tend to occur at low densities even where salinity conditions are favorable and rely mostly on other food sources derived from scavenging

Although salinity has its greatest effect on clam abundance indirectly through its effects on predator populations, salinity also affects other aspects of clam ecology. For example, laboratory and hatchery studies have shown that the development of the fertilized egg is the reproductive stage that is most sensitive to salinity. Salinities outside the optimal range can decrease the number of fertilized hard clam eggs that develop normally into larvae (USEPA, 1981).

Adult hard clams can tolerate a wide range of salinities, but grow most rapidly under certain optimal salinity conditions. As noted above, the poor productivity of the hard clam and oyster fisheries in eastern Great South Bay prior to 1931 was attributable to low bay salinities prior to the opening of Moriches Inlet (USEPA, 1982).

A study was conducted of the hard clam population in Moriches Bay during 1980 and 1981 to determine if the 1980 breach had any effect on hard clams (Turner, 1983). This study entailed a comparison of daily growth lines for specimens taken during and after the approximately one-year period when the breach was active. The results indicate that the breach decreased the rate of shell growth in clams in western Moriches Bay, but did not have any significant effect on shell growth in the eastern bay, so that shell growth rates were similar throughout the bay during the active period of the breach. The alteration of the salinity distribution caused by the breach would explain the observed shell growth patterns; the breach led to elevated salinities in the western bay, but did not affect this parameter in the eastern bay (where salinities were nearly oceanic both during and after the closure of the breach). However, other factors, such as temperature and tidal circulation, may have had some influence. It is important to note that the measurements of shell growth made during this investigation may not be reflective of tissue growth or reproductive vitality.

Deviation from the optimal salinity range reduces the clam's tolerance for other environmental stresses (such as high temperatures). Conversely, optimal temperature enhances tolerance for salinities outside the optimal range (USEPA, 1982).

Mussels prefer saltier waters, and would be prone to overgrow and smother oyster and clams in high salinity conditions (Van Popering and Glancy, 1947).

C. Water Temperature-Related Impacts

As discussed in Section 5.1.B, temperature and salinity have a synergistic effect on the ecology of hard clams. Of these two parameters, however, salinity has received much more attention in the scientific literature. The documents reviewed during this investigation indicate that adult hard clams tolerate a wide range of estuarine conditions (including temperature), to which they are exposed during different seasonal and weather conditions (USEPA, 1982). However, despite having a relatively wide tolerance range for temperature, hard clam growth is disrupted outside of the optimal temperature range. Interruptions in clam growth, as evidenced by the pattern of growth lines on the shells, occur both during summer periods of high temperature and during winter temperature minima (Greene, 1978; USEPA, 1981). Seasonal moderation of bay temperature, as would generally be expected to result from new inlet breaching, would tend to reduce growth interruptions induced by temperature extremes.

D. Impacts Related to Coastal Processes

Shellfish may be affected to a minor degree by the alteration in coastal processes resulting from an inlet breach. The increased tidal exchange associated with a new inlet would cause an increase in tidal current velocities, which would result in a overall increase in the coarseness of the benthic sediments in the bay. This would expand the area of sandy bay bottom, which clams prefer (Greene, 1978). However, shifting sands, as are found in the vicinity of inlets, tend to interfere with normal clam activity (USEPA, 1981).

5.2 *Finfish*

Studies concerning the impacts that new inlets have on finfish were found to be sparse. Some information is available with regard to how inlets affect larval and juvenile fish (as discussed below), but virtually no pertinent scientific studies have been uncovered which address impacts to adult fish. One investigation that was performed in the Galveston Bay system during the mid-1950s showed that the artificial opening of an inlet (Rollover Pass) had a noticeable effect on the adult populations of the dominant fish species, with some species increasing in abundance while other species declined (Reid, 1957). However, no conclusion was made with regard to the new inlet's overall impact on finfish stock.

The use of estuarine areas is an important phase in the life history of many marine organisms, including many commercially valuable fish. Some studies have postulated that fish recruitment to estuaries is accomplished strictly by passive mechanisms (i.e., transport entirely by currents), but the majority of recent studies suggest that active behavioral responses to physical factors and other stimuli are also important. For example, fishes spawning in the same offshore habitat may ultimately have different larval distributions, indicating that small behavioral differences among species may alter their susceptibility to passive transport (Boehlert and Mundy, 1988).

According to a summary paper by Boehlert and Mundy (1988), some studies suggest that the presence of an offshore salinity gradient is important to the recruitment of certain fish species. In years of high rainfall, the salinity gradient was well defined and recruitment levels were high. In years of low rainfall, recruitment levels were low due to a weakened salinity gradient. Other studies show that gradients of food abundance are a factor in the migration of some species into estuaries. A variety of other variables may also serve to stimulate migration toward estuary mouths.

The work described above indicates that some initial knowledge of the relationship between inlets and larval fish movement has been achieved. However, Miller (1988) has concluded that pertinent data are lacking with respect to the physical factors affecting the recruitment of fish to estuaries, because most physical oceanographers work in a scale that is too large to be applicable to the study of fish recruitment. Miller (1988) has also concluded that there is a lack of information concerning the behavioral responses of immature fish to these physical factors (e.g., currents, temperature, salinity, density, etc.); consequently, even if the necessary physical description were available concerning the water through which the fish migrate, prediction of the migration process would still not be possible. Thus, although it is clear that inlets are important to certain fish species, the dynamics of fish recruitment to estuaries are so poorly understood at the present time that more specific conclusions cannot be made. Clearly, a useful assessment of the impacts that a new inlet breach on Long Island's south shore would have on finfish recruitment is not currently possible.

As noted in Section 5.1.A, "small form" algae populations boomed during the years 1946 through 1951, when the flow through Moriches Inlet was greatly restricted. These algal blooms diminished visibility in bay waters to the point that fish could not see well enough to capture their food, which led to a decline in fish landings from the bay when these algae were present (Glancy, 1956).

The Texas Gulf coast has had a unique history of attempts to enhance local finfisheries by establishing "fish passes" through the barrier. Local fishing interests had long assumed that the creation of these passes automatically increased fish populations in the associated lagoons. Instead, the passes are best used as conduits to spawning grounds, and no net influx of fish occurs (Hoese, 1958). However, the passes are recognized to improve the environmental conditions in the bays by allowing tidal mixing with the Gulf and, thereby, preventing hypersalinity, excess temperatures, and stagnation during the dry season (Burr, 1945). This benefits the fish populations, but the conditions are not analogous to Long Island's south shore bays, which are fairly well-flushed and receive plentiful input of freshwater throughout the year via runoff and groundwater inflow from the mainland.

Although no pertinent scientific literature was uncovered during this investigation to document the association of adult fish and inlets, inlets and adjacent areas are generally recognized as having relatively high fish abundance and provide for high recreational fishing opportunities. Reports in local fishing periodicals (e.g., *The Fisherman*: Long Island, Metropolitan New York Edition) indicate that the new Moriches Bay inlet breach supported new recreational fishing activity during the summer of 1993.

5.3 *Other Animals*

A. Benthic Marine Animals

Four benthic surveys conducted between May 1981 and May 1982, following the closure of the 1980 breach, showed a general decline in the abundance of "opportunistic" species in Moriches Bay during the study period (Cerrato, 1986). Numerous studies have shown that this trend is typical of biological succession in marine ecosystems following a significant environmental disturbance (e.g., dredging, spoil disposal, raking, trawling). The first stage of succession involves the rapid repopulation of the disturbed area by certain "opportunistic" species, which have high reproductive and colonization capabilities. As time passes, the opportunist populations decline as these species are outcompeted by other species (termed "equilibrium" species). The closing of the breach essentially restored the environment to the pre-breach condition, and allowed the equilibrium species to assume dominance of the bay once again.

B. Shore Birds

Studies of the 1987 inlet breach of Nauset Beach, Massachusetts, provides some interesting information regarding the effects that such an event can have on shore birds (Wood, 1991). The breach separated the southerly portion of the barrier as an island, which was effectively isolated from all access except via watercraft. This newly-formed island became increasingly attractive to least terns (*Sterna antillarum*) and piping plovers (*Charadrius melodus*), both of which are Federally-designated endangered species. However, most of the original nesting pairs that were established following the breach were either destroyed by subsequent washovers or fell victim to predation by foxes and skunks that were trapped on the island. This isolated beach also became a popular destination for boaters, which created an additional conflicts with the shore bird colonies.

Piping plovers, least terns, and roseate terns (*Sterna dougallii*) use the unvegetated or sparsely vegetated area between the high tide line and the base of the dunes for nesting habitat (NYS Department of State, 1991). Since an actively migrating inlet is continually creating new areas of sandy beach on the up-drift barrier (see Section 4.4), inlet breaching can provide a benefit to shore birds in terms of the creation of new habitat. However, this potential benefit must be balanced against habitat areas that may have been destroyed by the new inlet cut.

C. Waterfowl

Waterfowl may be affected by the breaching of a new inlet in several ways. Salt marshes in the bay serve as important feeding and nesting areas for a number of waterfowl, including herons, egrets,and other wading birds. Consequently, the beneficial effect that inlet breaching has on the creation and productivity of back-barrier wetlands (see Section 5.4 below) would also tend to be of long-term benefit to these avian species.

Relatively short-term impacts to waterfowl can result from the changes induced in the physical characteristics of the bay, although it is not clear whether these changes would be beneficial or detrimental on an overall basis. As is discussed in Section 3.3, a breach would tend to have a moderating effect on seasonal extremes in bay temperature by keeping these waters cooler in the summer and slightly warmer in the winter. This would benefit certain waterfowl (such as marsh ducks) that overwinter in the bay and which require ice-free, shallow water areas to feed. Other varieties of waterfowl (such as diving ducks) which can utilize off-shore feeding areas would receive less benefit from the decreased extent of ice accumulation that would be expected to result from inlet-induced winter temperature increases in the bay (NYS Department of Environmental Conservation, 1952). Acting in opposition to this beneficial impact is the effect that increased bay salinity would have on waterfowl. Embayments that are less saline generally constitute the best habitat for waterfowl. In fact, it was suggested that the sealing of Moriches and Shinnecock Inlets would provide the greatest benefit to waterfowl in terms of habitat value, although it was recognized that such action would not be a realistic option for numerous other reasons, including adverse impacts on bay water quality, shellfisheries, fishing access to the ocean, and other factors (NYS Department of Environmental Conservation, 1952).

5.4 *Wetlands and Seagrasses*

The most significant process of new tidal marsh formation behind barrier beaches involves inlet dynamics. Specifically, flood tidal deltas created by sand carried through inlets serve as the platforms on which new marshes may become established. The majority of salt marsh systems behind barrier beaches on the East Coast originally developed on old flood tidal deltas (Leatherman, 1982). The marsh islands and back barrier marshes in Shinnecock Bay and eastern Great South Bay are clearly associated with flood tidal deltas of former inlets (Leatherman and Allen, 1985; Leatherman, 1989).

As an inlet migrates in response to littoral processes, the flood tidal delta also migrates, creating a string of back-barrier delta deposits. When an inlet closes (as most temporary storm-created inlets do), or as formerly active deltas become further removed from a migrating inlet, these shoals will evolve into salt marshes or underwater grass beds if their elevation is sufficient (Godfrey, 1976).

The relationship between inlet status and vegetative communities discussed above is confirmed in an investigation of pollen samples in cores taken from a series of transects along the barrier beaches to the east of Fire Island Inlet (Clark, 1986). Inlets affected vegetation in the study area by altering the tidal range and salinity of the back-barrier lagoons, and by providing new substrate for marsh establishment when flood tidal deltas were abandoned by inlet channels. Salt marshes fringed the back barrier lagoons only when inlets were open and saline/ tidal conditions prevailed (1760 to 1835; and 1931 to present in Moriches Bay). The loss of tidal variation in water level associated with the closure of inlets resulted in the rapid colonization of former high salt marsh areas by sedge-dominated wet meadows and shrub thickets. This plant community reflects low salinity conditions, often approaching a freshwater state. The changes in vegetative communities related to changes in inlet status were noted to be very rapid.

Maintaining stabilized inlets interferes with long-term sediment dynamics, and precludes the formation of new marshes both directly and indirectly. The dredging of flood tidal deltas at existing inlets directly impacts the potential for the creation of new wetlands and expansion of existing wetlands. Actions undertaken to impede the genesis of new inlets or to promptly close breaches indirectly prevents the formation of associated flood tidal deltas, which would serve as new substrate for future wetlands (Leatherman, 1989).

A study conducted along the North Carolina shoreline indicates that tidal marsh productivity is affected by inlet processes (Godfrey and Godfrey, 1975). Tidal marsh areas near active, migrating inlets will stay in the early stages of vegetative succession. Under these conditions, organic production within the marsh and the rate of its export to the estuary are high. In comparison, long-term stability, either naturally or artificially created, will result in decreased productivity.

Beds of eelgrass (*Zostera marina*) cover some portions of the subtidal zone in Long Island's south shore bay system, and are known to serve as important habitats for a variety of juvenile and adult finfish and shellfish. The depth of sunlight penetration was found to be the most important factor governing the distribution and growth of eelgrass in Great South Bay (Greene, et.al., 1978). Eelgrass beds are thin or non-existent in areas of high turbidity, and are also adversely affected by high summer temperatures. The densest eelgrass beds are found in the western part of Great South Bay, where a high degree of tidal flushing due to proximity to Fire Island and Jones Inlets results in waters that are relatively clear.

Shifting sands associated with the flood tidal delta of a new inlet can adversely affect existing sub-tidal vegetation in adjacent areas. This impact was noted following a breach that formed on the Nantucket Island barrier in Massachusetts. The inlet's mobile flood tidal delta stifled eelgrass beds, thereby adversely affecting nursery areas for bay scallops (Tiffney and Benchley, 1987).

6. MISCELLANEOUS IMPACTS

6.1 *Navigation*

The effect that new inlet breaches have on navigation can be positive or negative. The bay-side shoaling that is associated with the formation of the flood tidal delta of a new inlet can create a hazard to navigation, particularly at low tidal stages or during periods of peak tidal current (Wood, 1991; Fessenden and Scott, 1989; Tiffney and Benchley, 1987). This problem has been the topic of considerable debate over the recent past with respect to the existing inlets on Long Island's south shore, particularly the three easterly inlets. In the case of very active delta deposits, the position of the channel could change rapidly. It is reported that the channel through the Nauset breach would sometimes shift dramatically between consecutive tidal cycles during the period shortly after the breakthrough (Wood, 1991). Shoals can form at other locations in the bay due to the deposition of material eroded from the mainland shoreline by ocean waves passing through a new inlet, as occurred in Chatham Harbor, Massachusetts, following the January 1987 breach (Fessenden and Scott, 1989). In that case, the shoaling impaired the use of a marina, which necessitated a significant amount of dredging to maintain operations.

The formation of a new inlet can have a beneficial effect on navigation by creating an alternate (and possibly more convenient) route between the bay and ocean. Moriches Inlet is a prime example of a passage that is heavily utilized by recreational fishermen, who would otherwise have lengthy and perhaps prohibitively long trips to the open ocean if the inlet did not exist. The Nauset breach on Cape Cod reportedly saved an hour and a half per trip for fishermen traveling between Chatham Harbor and the Atlantic. However, that shortcut also presented hazards, including tricky currents, in addition to the rapidly shifting shoals discussed above (Wood, 1991). This combination of divergent navigational impacts that are often associated with a new inlet (i.e., the appeal of a more convenient route, coupled with a number of potentially significant boating hazards) creates a concern that some boaters, particularly less experienced recreational boaters, could be unknowingly lured into a dangerous situation.

A study of Drum Inlet on the North Carolina barrier island chain concluded that the project to artificially re-establish this inlet did not provide the anticipated improvement in the convenience of fishing access between the sound and the Atlantic Ocean, which was one of the originally-stated objectives of the work (Blankinship, 1976). However, the author provided no further elaboration on this point; he may be referring to the need to perform additional work to improve navigability (i.e., channel straightening and regular maintenance dredging).

As discussed in Section 3.4, the tidal range within the adjacent bay would generally increase as a result of an inlet breach, which can lead to a potential increase in flooding during high tidal stages. However, the related drop in the elevation of low water may cause an impact to navigation throughout the bay. If decreased low tide levels result in channel depths that are less than the design depths, redredging of these channels may become necessary (Douma and Wicker, 1965).

6.2 *Economic Factors*

Economic factors should always be fully considered in deciding how to respond to a new inlet breach. Unfortunately, however, the economic consequences of a breach are even more difficult to assess than the environmental effects. The economic impacts are very site-specific, and would depend on the unique combination of environmental factors that pertain to a given breach, including both positive and detrimental impacts that may partially offset one another. Given this complexity, it is not surprising that there does not appear to be any scientific literature available which addresses the economic impacts of new inlets.

The economic expenditures associated with the closure of a breach should be relatively easy to determine on the basis of materials and labor expenses. For example, the closure of the 1980 Moriches Bay breach was estimated to have cost $11 million (Tanski and Bokuniewicz, 1988). However, recent developments concerning the closure of the 1992 breach at Westhampton Beach have added an element of uncertainty to the equation. In that case, local baymen have filed a suit to halt the ongoing work sponsored by the U.S. Army Corps of Engineers to seal the new inlet. The suit is based on the allegation that the closure of the breach will cause a decline in the water quality in Moriches Bay and, thereby, adversely affect shellfish resources that the baymen rely upon for their livelihoods. If this suit is upheld, cost impact analyses for inlet closure projects would become much more complicated because decision makers would be compelled to consider vaguely defined potential losses of economic benefit in addition to the hard costs of the engineering works.

The physical work to close a breach may itself have unintended adverse impacts. For example, the project to close the 1980 Moriches Bay breach involved the use of trucks to carry fill material obtained from an on-shore sand mine. The intent behind selecting land-based construction (rather than hydraulic pumping from the sea or bay floor, which is the usual method) was reportedly to expedite mobilization by using equipment available locally to the contractor and to reduce possible down time (Sorensen and Schmeltz, 1982). However, the net weight of these trucks exceeded the weight limit of the Beach Lane Bridge over Quantuck Canal (between Moriches and Shinnecock Bays); some of the trucks reportedly exceeded the bridge's limit by 14 tons. Approximately 200 truckloads per day were being transported to the job site at the time of the report (Fetherston, 1980). Overweight trucks can accelerate the deterioration of roads and bridges, increasing maintenance requirements and endangering public safety.

If a decision is made to allow a breach to remain open, the need for engineering works and/or maintenance dredging may eventually arise. Black (1987) has noted that, although the inlet stabilization projects on Long Island's barrier beach have generally proven effective, all require periodic maintenance. Such maintenance will entail monetary expenditures which can be substantial, depending on the inlet's hydraulic stability, the rate of littoral sand supply, and other factors.

7. SUMMARY OF IMPACTS

The environmental impacts of tidal inlet breaching are summarized below. These have been placed into general categories, based on whether the effect is beneficial, detrimental, neutral, variable, or inadequately defined.

7.1 *Beneficial Impacts*

The following consequences of tidal inlet breaching have a generally beneficial environmental impact:

- increased tidal flushing, which: improves the water quality of the bay, reduces the accumulation of deleterious substances and decreases the chances for algal blooms; and reduces turbidity and increases the area of bay bottom suitable for the growth of eelgrass
- increased rate of barrier beach migration, which maintains barrier width and allows the barrier system to adjust its position in response to sea level rise
- increased salinity in the bay, which allows for an accelerated rate of shellfish growth and improved larval development
- seasonal moderation of bay temperature, which would tend to reduce growth interruptions induced by temperature extremes (especially in shellfish)
- potentially increased recruitment of juvenile and larval fish to the bay
- increased areas for recreational and commercial fishing activity (inlets are generally recognized as important fishing areas)
- increased rate of formation of new areas of tidal wetlands on the back-barrier
- increased rate of overall productivity of marshes in the bay

7.2 *Adverse Impacts*

The following consequences of tidal inlet breaching have a generally detrimental environmental impact:

- increased salinity, which allows certain shellfish predators to penetrate further into the bay
- increased tidal exchange between the bay and ocean, which allows the water level in the bay to rise higher, increasing the flooding potential along the bay shore, especially during short period events (e.g., semidiurnal tidal fluctuations and typical hurricanes); the effect on water levels during long-period storm events such as northeasters is less pronounced
- potentially increased energy of waves arriving at the mainland shoreline, which would result in an increased rate of erosion
- interruption of the littoral transport system by the deposition of sand in the tidal deltas of the new inlet, which typically increases the rate of shoreline erosion at down-drift locations (this is exacerbated by the presence of groins up-drift)
- increased tidal flushing, which may cause the larvae of certain bay organisms (particularly shellfish) to be carried out to the ocean prior to settlement
- potential burial of portions of the bay floor near the new inlet by shifting sands associated with flood tidal delta deposits, which may destroy clam beds and/or inhibit the growth of eelgrass (which must be balanced against the potential benefits of increased salinity and flushing)

7.3 *Neutral, Variable or Inadequately Defined Impacts*

The following consequences of tidal inlet breaching have a environmental impact that is neutral, variable, or inadequately defined:

- decreased average temperature of the bay, with an effect on shellfish resources that has not been adequately studied, but which will vary from species to species
- alterations in the progression of the tidal wave through the bay system (i.e., the time of high or low tide at a given location), which is usually neither beneficial nor detrimental

- possible refraction of incoming waves due to nearshore tidal currents and bathymetric changes associated with the new inlet's ebb tidal delta, which may cause localized increases in shoreline erosion and deposition rates

- possible increase or decrease in the rate of shoaling of adjacent inlets, which would tend to occur gradually following the occurrence of a breach; hydraulically-connected inlets may experience increased shoaling due to some tidal prism being lost to the new inlet, while inlets at down-drift locations may experience decreased shoaling due to the accumulation of littoral sand in the new inlet's tidal deltas

- undetermined impacts on adult finfish populations

- possible isolation of habitats suitable for protected shorebird species, which is a complex issue that cannot presently be generically classified as beneficial or detrimental, due to scarce data and conflicting existing information

- possible effects on waterfowl populations, which cannot presently be classified as having an overall beneficial or detrimental effect, due to conflicting information

- potential encroachment of salt marsh vegetation into areas that had previously been occupied by brackish or freshwater wetland plants, which has not been fully assessed in terms overall environmental benefit or detrimental impact

- navigational impacts that may be beneficial (e.g., more convenient route to the ocean) or detrimental (e.g., increased shoaling associated with the new inlet's flood tidal delta, and possible increases in the shoaling of hydraulically-connected inlets), or neither or both

- economic impacts that cannot be summarized on a generic basis

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APPENDIX A

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Mark Byrnes	Louisiana State University
Fred Camfield	U.S. Army Corps of Engineers, Coastal Engineering Research Center, Vicksburg
Jack Clark	Massachusetts State Coastal Zone Management Program
B.J. Copeland	North Carolina State Sea Grant
Robert Dalrymple	University of Delaware
DeWitt Davies	Suffolk County Department of Planning
Robert Dean	University of Florida
Robert Dolan	University of Virginia
John Fisher	North Carolina State University
Duncan Fitzgerald	Boston University
Jeff Gebert	U.S. Army Corps of Engineers, Philadelphia
Graham Giese	Woods Hole Oceanographic Institute
Bill Hettler	National Marine Fisheries Service
Dick Hoese	University of Southwestern Louisiana
Scott Holt	Marine Science Institute, Port Aransas, Texas
Tom Jarret	U.S. Army Corps of Engineers, Willmington
Jeff Kassner	Town of Brookhaven, New York
Stephen Leatherman	University of Maryland
Sandy McFarland	Town of Orleans, Massachusetts
John Miller	North Carolina State University
Andrew Morang	U.S. Army Corps of Engineers, Coastal Engineering Research Center, Vicksburg
Robert Morton	University of Texas

APPENDIX A (continued)

LIST OF PERSONS CONTACTED DURING THIS INVESTIGATION

Name	Affiliation
Gil Nersesian	U.S. Army Corps of Engineers, New York
Orrin Pilkey	Duke University
Carl Rafk	Barnstable County, Massachusetts, Cooperative Extension
Spencer Rogers	North Carolina State Sea Grant
Margaret Swanson	Town of Chatham, Massachusetts
Jay Tanski	New York State Sea Grant
George Ward	University of Texas
Timothy Wood	Cape Cod Chronicle, Chatham, Massachusetts
Mike Wutkowski	U.S. Army Corps of Engineers, Willmington
John Zarudsky	Town of Hempstead, New York

APPENDIX B

LIST OF LIBRARIES AND DOCUMENT DEPOSITORIES USED DURING THIS INVESTIGATION

Marine Sciences Research Center, State University of New York at Stony Brook

State University of New York At Stony Brook, main library system

Suffolk County Community College, Selden, New York

Coastal Engineering Archives, University of Florida, Gainsville, Florida

U.S. Army Corps of Engineers, Waterways Experiment Station, Technical Reference Unit, Vicksburg, Mississippi

U.S. Army Corps of Engineers, Waterways Experiment Station, Reports Distribution Center, Vicksburg, Mississippi

ational Sea Grant Depository, University of Rhode Island, Bay Campus at arragansett

rida Sea Grant Publications, University of Florida at Gainsville

neering Societies Library at the United Engineering Center, New York, New